Using Accelerometers in Low *g* Applications
by Charles Kitchin

INTRODUCTION

Accelerometers can be used in a wide variety of low *g* applications such as tilt and orientation, vibration analysis, motion detection, etc. This application note explains how to best apply the ADXL50 (50 *g*) and ADXL05 (5 *g*) accelerometers when measuring signals at the low end of their respective full-scale ranges. Although each accelerometer is specified according to its full scale (clipping) *g* level, the limiting resolution of the device, i.e., its minimum discernible input level, is extremely important when measuring low *g* accelerations.

The limiting resolution is predominantly set by the measurement noise "floor" which includes the ambient background noise and the noise of the accelerometer itself. The level of the noise floor varies directly with the bandwidth of the measurement. As the measurement bandwidth is reduced, the noise floor drops, improving the signal-to-noise ratio of the measurement and its limiting resolution.

DEVICE BANDWIDTH VS. MEASUREMENT RESOLUTION

The output noise of the ADXL50 and ADXL05 scales with the square root of the measurement bandwidth. The maximum amplitude of the noise, its peak-to-peak value, approximately defines the worst-case resolution of a measurement. The peak-to-peak noise is approximately equal to 6.6 times its rms value (for an average uncertainty of 0.1%).

The bandwidth of the accelerometer can be easily reduced by adding low-pass or bandpass filtering. Figure 1 shows the noise vs. bandwidth characteristics of the ADXL50 and ADXL05 devices.

As shown by the figure, device noise drops dramatically as the operating bandwidth is reduced. For example, when operated in a 1 kHz bandwidth, the ADXL05 typically has a peak-to-peak noise level of 130 m*g*. With ±5 *g* applied accelerations, this 130 m*g* resolution limit is normally quite satisfactory; but for
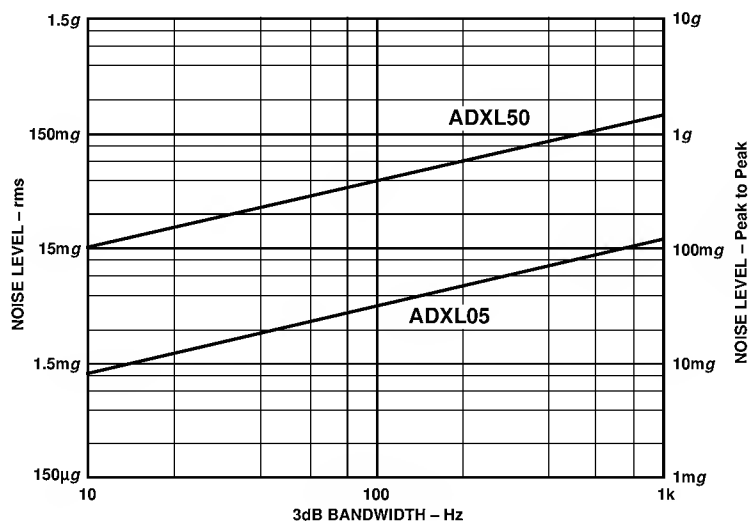

Figure 1. Noise Level vs. 3 dB Bandwidth

smaller acceleration levels the noise is now a much greater percentage of the signal. As shown by Figure 1, when the device bandwidth is rolled off to 100 Hz, the peak-to-peak noise level is reduced to approximately 40 mg, and at 10 Hz it is down to 10 mg.

Alternatively, the signal-to-noise ratio may be improved considerably by using a microprocessor to perform multiple measurements and then compute the average signal level. When using this technique, the signal level will be increased directly with the number of measurements while the noise will only increase by their square root. For example, with 100 measurements, the signal-to-noise ratio will be increased by a factor of 10 (20 dB).

Low-Pass Filtering
The bandwidth of either accelerometer can be reduced by providing post filtering. Figure 2 shows how the buffer amplifier can be connected to provide 1-pole post filtering,

0 g offset trimming, and output scaling. Two tables are included with the figure which provide practical component values for various full-scale g levels and approximate circuit bandwidths. For bandwidths other than those listed, use the formula:

$$Capacitor\ C4\ (Farads)\ =\ \frac{1}{2\pi \times R3(\Omega) \times 3dB\ BW\ (Hz)}$$

or simply scale the value of capacitor C4 accordingly, i.e., for an application with a 50 Hz bandwidth, the value of C4 will need to be twice as large as its 100 Hz value. If further noise reduction is needed while maintaining the maximum possible bandwidth, then a 2- or 3-pole post filter is recommended. These provide a much steeper roll-off of noise above the pole frequency. Figure 3 shows a circuit that uses the buffer amplifier to provide 2-pole post filtering. Component values for the 2-pole filter were selected to operate the buffer at unity gain.

ADXL50 COMPONENT VALUES FOR VARIOUS FULL-SCALE RANGES AND BANDWIDTHS

FULL SCALE	mV per g	3dB BW (Hz)	R1a kΩ	R1b kΩ	R3 kΩ	R2 kΩ	C4 µF
±10g	200	100	5	21.5	249	100	0.0068
±20g	100	100	5	23.7	137	100	0.01
±10g	200	10	5	21.5	249	100	0.068
±20g	100	10	5	23.7	137	100	0.01

3dB BW = $\frac{1}{2\pi\ R3\ C4}$

ADXL05 COMPONENT VALUES FOR VARIOUS FULL-SCALE RANGES AND BANDWIDTHS

FULL SCALE	mV per g	3dB BW (Hz)	R1a kΩ	R1b kΩ	R3 kΩ	R2 kΩ	C4 µF
±1g	2000	10	10	24.9	301	100	0.056
±2g	1000	100	10	35.7	200	100	0.0082
±4g	500	200	10	35.7	100	100	0.0082
±5g	400	300	10	45.3	100	100	0.0056

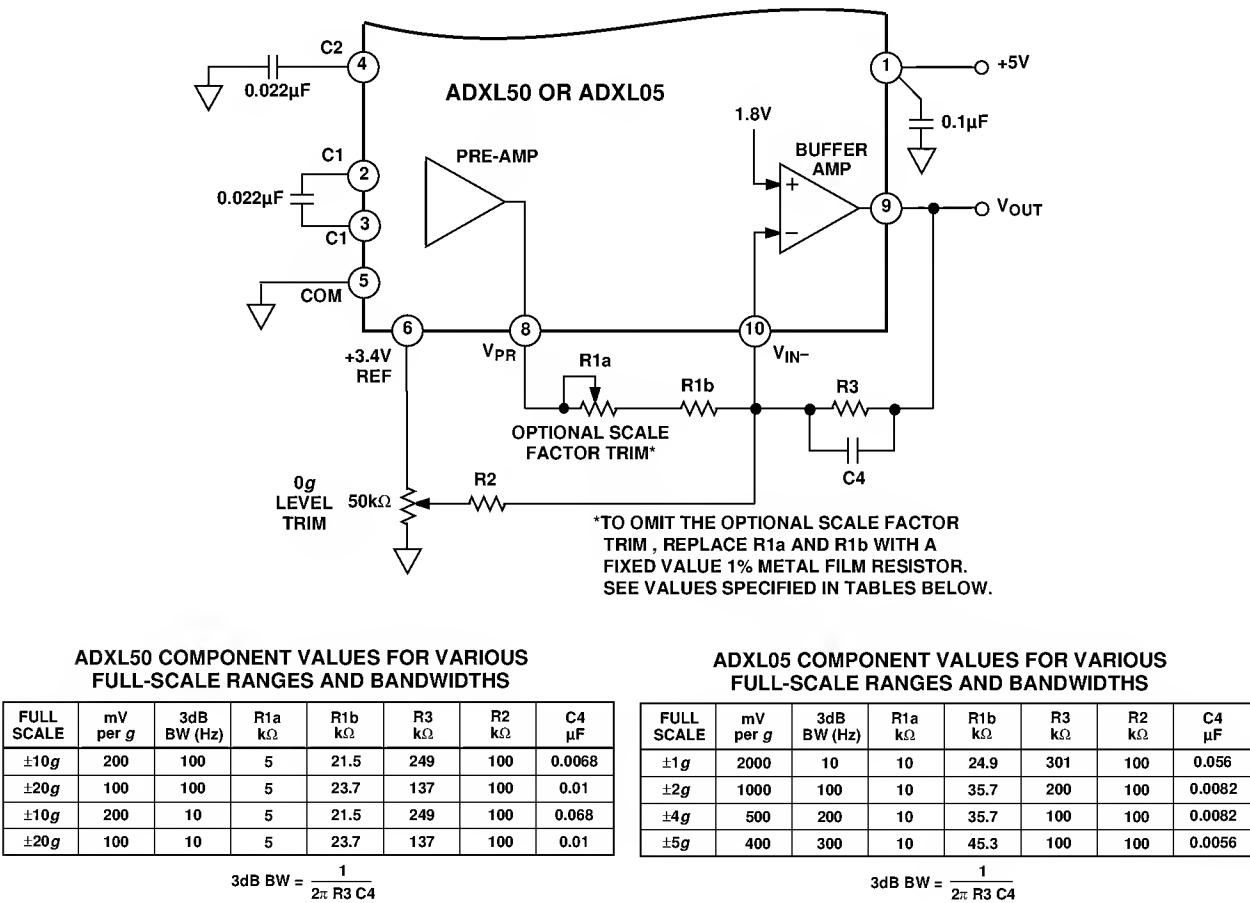3dB BW = $\frac{1}{2\pi\ R3\ C4}$

Figure 2. Using the Buffer Amplifier to Provide 1-Pole Post Filtering Plus Scale Factor and 0 g Level Trimming

Capacitors C3 and C4 were chosen to provide 3 dB band-widths of 10 Hz, 30 Hz, 100 Hz, and 300 Hz.

In this configuration, the nominal buffer amplifier output will be +1.8 V ± the scale factor of the accelerometer, either 19 mV/g for the ADXL50 or 200 mV/g for the ADXL05. An AD820 external op amp allows noninteractive adjustment of 0 g offset and scale factor. The external op amp offsets and scales the output to provide a +2.5 V ± 2 V output over a wide range of full-scale g levels.

Additional Noise Reduction Techniques

In addition to reducing circuit noise, any electro-magnetic interference (EMI) needs to be considered. Shielded wire should be used for connecting the accelerometer to any equipment or circuitry that is more than a few inches away. A common problem is that of 60 Hz pickup from ac line voltage. This can be minimized by physically moving the device away from power leads, or if that is not practical, using proper shielding and grounding techniques. In most cases, it is advisable to ground the cable's shield at only one end and connect a separate common lead between the circuits; this will help to prevent ground loops. Also, if the accelerometer is inside or near a metal enclosure, this should be grounded as well.

Another area to consider is mechanical resonance of the overall measurement system. The use of a highly flexible shielded wire will greatly help to prevent secondary resonance effects of wire vibrating at its natural frequency. A shielded cable with a silicone jacket and silicone insulation such as that produced by Cooner Wire Company of Chatsworth, California, is recommended.
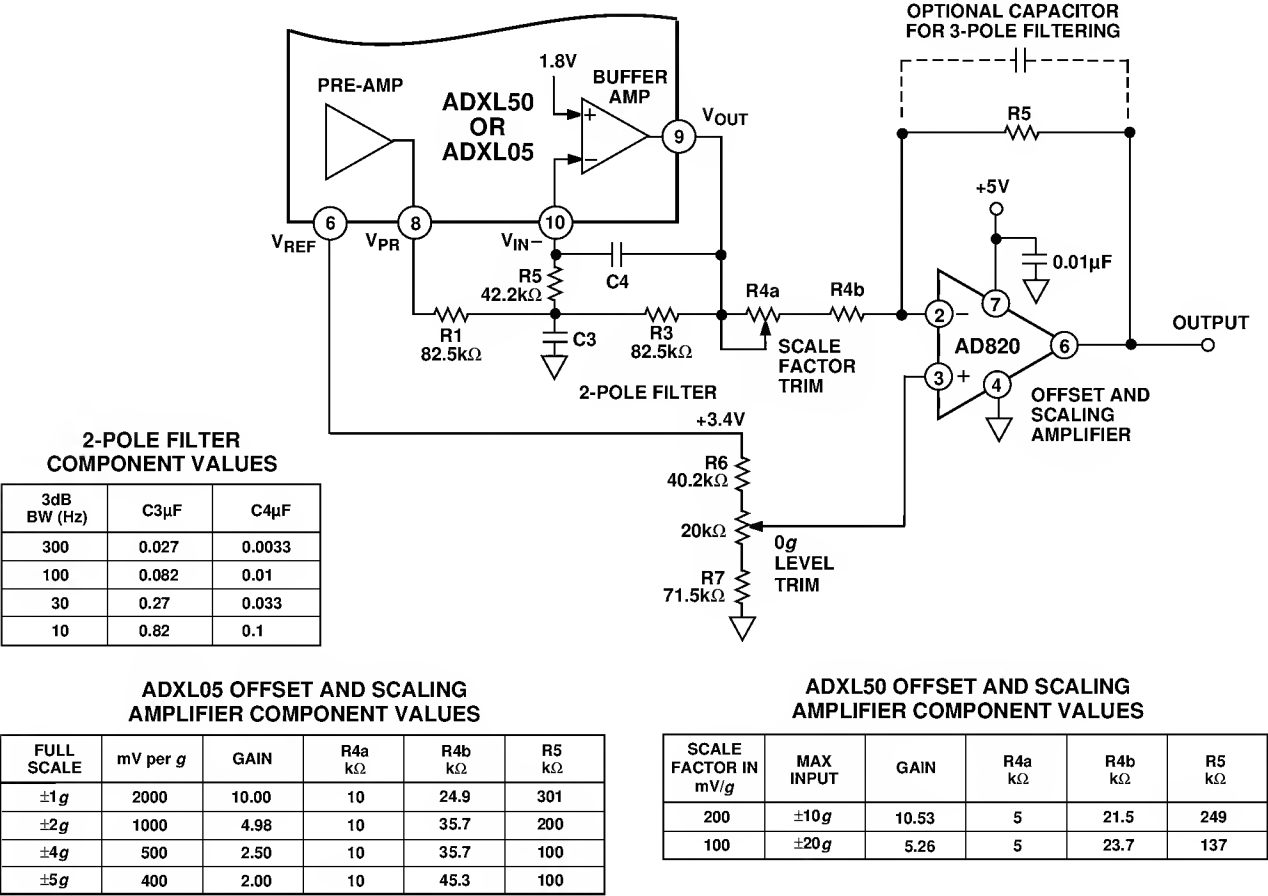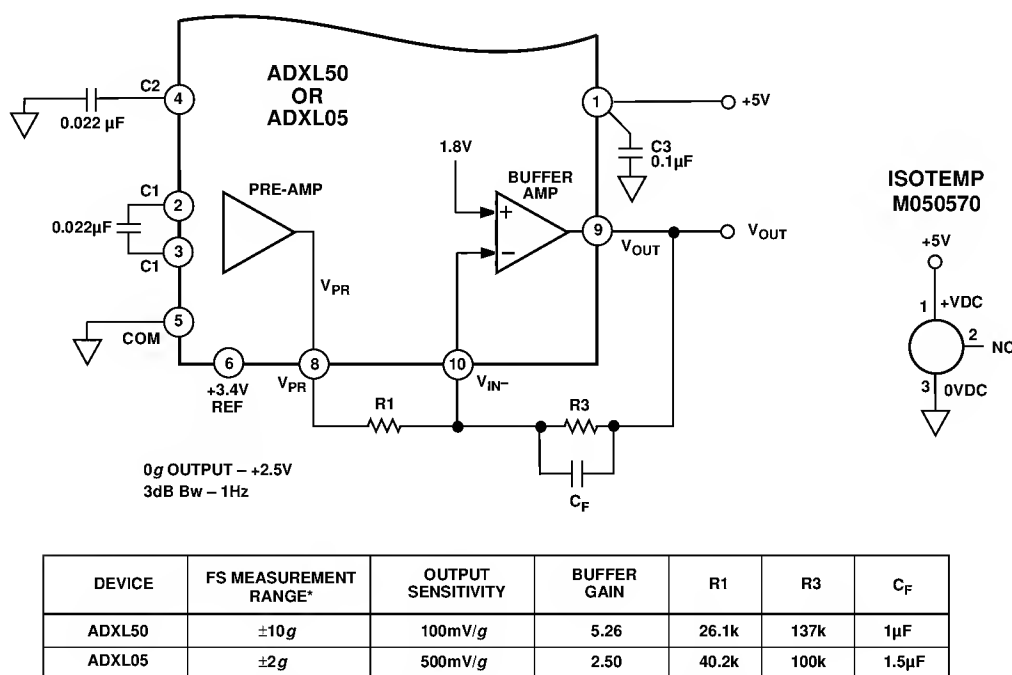

2-POLE FILTER COMPONENT VALUES

3dB BW (Hz)	C3µF	C4µF
300	0.027	0.0033
100	0.082	0.01
30	0.27	0.033
10	0.82	0.1

ADXL05 OFFSET AND SCALING AMPLIFIER COMPONENT VALUES

FULL SCALE	mV per g	GAIN	R4a kΩ	R4b kΩ	R5 kΩ
±1g	2000	10.00	10	24.9	301
±2g	1000	4.98	10	35.7	200
±4g	500	2.50	10	35.7	100
±5g	400	2.00	10	45.3	100

ADXL50 OFFSET AND SCALING AMPLIFIER COMPONENT VALUES

SCALE FACTOR IN mV/g	MAX INPUT	GAIN	R4a kΩ	R4b kΩ	R5 kΩ
200	±10g	10.53	5	21.5	249
100	±20g	5.26	5	23.7	137

Figure 3. Two-Pole Filtering Circuit with Gain and 0 g Offset Adjustment

OFFSET DRIFT CONSIDERATIONS

When using an accelerometer with a dc (gravity sensing) response, the 0 g offset level will exhibit some temperature drift. When the accelerometer must measure low g levels over wide temperature ranges, the 0 g drift can become large in proportion to the signal amplitude. If a dc response is truly needed, there are a number of design options available. One very straightforward approach is to use a low cost crystal oven to maintain the accelerometer at a constant temperature. These ovens are particularly useful in high accuracy tilt applications. After the circuit has been built and is operating correctly, the crystal oven can be mounted over the accelerometer and powered off the same +5 V power supply. Figure 4 shows the basic circuit.

The ovens may be purchased from Isotemp Research, Inc., P.O. Box 3389, Charlottesville, VA 22903, phone 804-295-3101. For more details on crystal oven compensation, refer to application note AN-385.

Other methods for 0 g drift compensation include using a low cost temperature sensor such as the AD590 to supply a microprocessor with the device temperature. If the drift curve of the accelerometer is stored in the µP, then a software program can be used to subtract out the drift. This method works well, removing both the linear and nonlinear components of the drift. But due to device-to-device variation, it requires that the drift curve of each individual accelerometer be known (or measured). Alternatively, various drift compensation circuits can be used to subtract out the linear portion of the accelerometer's drift by using a temperature sensor and op amp to supply a small compensation current. This hardware approach does not use a µP but does require calibrating the compensation circuitry for each device. For more details on software and hardware drift compensation, refer to application note AN-380.

DEVICE	FS MEASUREMENT RANGE*	OUTPUT SENSITIVITY	BUFFER GAIN	R1	R3	C_F
ADXL50	±10g	100mV/g	5.26	26.1k	137k	1µF
ADXL05	±2g	500mV/g	2.50	40.2k	100k	1.5µF

*FS RANGE NUMBERS ARE CONSERVATIVE TO ALLOW FOR V_{PR} 0g TOLERANCE.

Figure 4. Low g DC Coupled (Tilt) Circuit Using Crystal Oven Compensation

AC Coupling

If a dc (gravity) response is not required—for example in motion sensing or vibration measurement applications—ac coupling can be used between the preamplifier output and the buffer input as shown in Figure 5.

Because ac coupling removes the dc component of the output, the preamp output signal may be amplified considerably without increasing the 0 g level drift. If capacitor C5 is added to the ac coupling circuit, forming a 1-pole low-pass filter, then a bandpass function is provided that will attenuate any signals other than those within the pass band. A typical ac coupled frequency response is shown in Figure 6.

The low frequency roll-off, F_L, due to the ac coupling network is:

$$F_L = \frac{1}{2 \pi R1 C4}$$

In this case, the high frequency roll-off, F_H, is determined by the 1-pole post filter R3, C5.

If ac coupling is used, the self-test feature must be monitored at V_{PR}, rather than at the buffer output (since the self test output is a dc voltage).
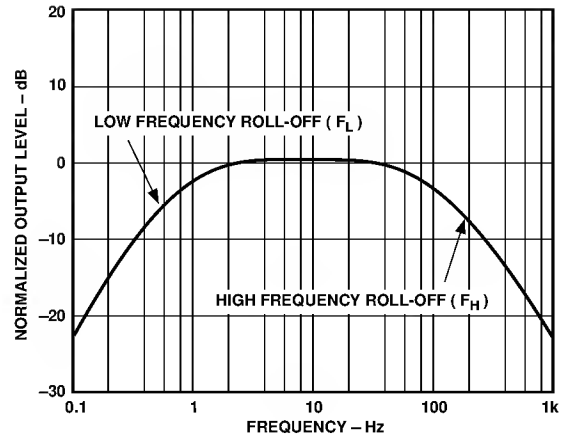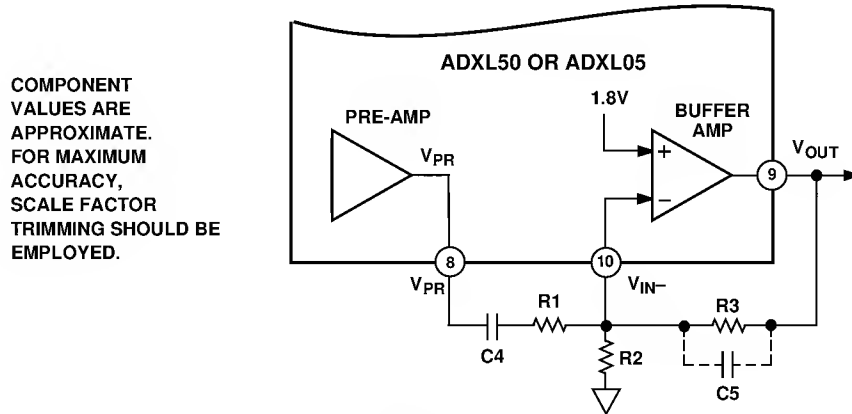

Figure 6. Typical Output vs. Frequency Curve when AC Coupling V_{PR} to the Buffer

Note that capacitor C4 should be a nonpolarized, low leakage type. If a polarized capacitor is used, tantalum types are preferred, rather than electrolytic. With polarized capacitors, V_{PR} should be measured on each device and the positive terminal of the capacitor connected toward either V_{PR} or V_{IN}—whichever is more positive.

COMPONENT VALUES ARE APPROXIMATE. FOR MAXIMUM ACCURACY, SCALE FACTOR TRIMMING SHOULD BE EMPLOYED.

ADXL50

SCALE FACTOR IN mV/g	DESIRED LOW FREQUENCY LIMIT, F_L	R1 VALUE IN kΩ	CLOSEST C4 VALUE	DESIRED HIGH FREQUENCY LIMIT, F_H	R3 IN kΩ	CLOSEST C5 VALUE	VALUE OF R2 FOR +2.5V 0g LEVEL
200	30	24	0.22µF	300	249	0.002µF	640kΩ
100	10	24	0.68µF	300	127	0.0039µF	326kΩ
200	3	24	2.2µF	100	249	0.0068µF	640kΩ
100	1	24	6.8µF	100	127	0.01µF	326kΩ
200	0.1	24	68µF	10	249	0.068µF	640kΩ

ADXL05

SCALE FACTOR IN mV/g	DESIRED LOW FREQUENCY LIMIT, F_L	R1 VALUE IN kΩ	CLOSEST C4 VALUE	DESIRED HIGH FREQUENCY LIMIT, F_H	R3 IN kΩ	CLOSEST C5 VALUE	VALUE OF R2 FOR +2.5V 0g LEVEL
1000	30	49.9	0.10µF	300	249	0.002µF	640kΩ
200	30	249	0.022µF	300	249	0.002µF	640kΩ
1000	3	49.9	1.0µF	100	249	0.0068µF	640kΩ
200	1	249	0.68µF	100	249	0.0068µF	640kΩ
200	0.1	249	6.8µF	10	249	0.068µF	640kΩ

Figure 5. AC Coupling the V_{PR} Output to the Buffer Input

GAIN SELECTION ISSUES

The uncommitted amplifier incorporated into the ADXL50 and ADXL05 devices allows the user to readily set the scale factor to the desired voltage output per g of applied acceleration. However, some caution is advised in not setting the scale factor, too high as the output buffer could run out of "headroom," i.e., the buffer's output can go as low as 0.25 volts and as high as 4.75 volts. This means the buffer's maximum output swing is +2.5 V ± 2.25 V. If the gain is too high, the buffer can clip on periodic transient accelerations; or it can clip due to the fact that the 0 g offset drift is also amplified along with the signal.

Therefore, use only enough gain in the buffer as is necessary to override any transmission losses between the accelerometer and any following circuitry (i.e., to keep the system's signal to noise ratio high).

Using the Earth's Gravity to Calibrate the Accelerometer

Both the 0 g offset and scale factor of the ADXL50 and ADXL05 devices may be roughly calibrated by using the 1 g (average) acceleration of the Earth's gravity. Figure 7 shows how gravity and package orientation affect the output polarity. Note that the output polarity is that which appears at V_{PR}; the output at V_{OUT} will have the opposite sign (due to the buffer amplifier's inverting configuration). With its axis of sensitivity in the vertical plane, the accelerometer should register a 1 g acceleration, either positive or negative, depending on orientation. With the axis of sensitivity in the horizontal plane, no acceleration (0 g) should be indicated.

Calibrate the accelerometer by placing it on its side with its axis of sensitivity oriented as shown in "a." The 0 g offset potentiometer, R_T, (as shown in Figure 2) is then roughly adjusted for midscale: +2.5 V at the buffer output.
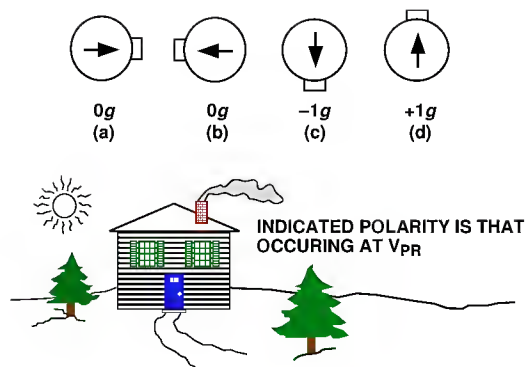

Figure 7. Using the Earth's Gravity to Calibrate the ADXL50 and ADXL05 Accelerometers

If the optional scale factor trimmer, R1a, is to be used, it should be adjusted next. The package axis should be oriented as in "c" (pointing down) and the output reading noted. The package axis should then be rotated 180° to position "d" and R1a adjusted so that the output voltage indicates a change of 2 gs in acceleration. For example, if the circuit scale factor at the buffer output is 200 mV per g, then the scale factor trim should be adjusted so that an output change of 400 mV is indicated.

Adjusting the circuit's scale factor will have some effect on its 0 g level, so this should be readjusted, as before, but this time checked in both positions "a" and "b." If there is a difference in the 0 g reading, a compromise should be selected so that the reading in each direction is equal distant from +2.5 V. Scale factor and 0 g offset adjustments should be repeated until both are correct.

APPLICATIONS ASSISTANCE

For applications assistance contact Charles Kitchin, Accelerometer Applications, Analog Devices Semiconductor, 831 Woburn St., Wilmington, MA 01887. Phone: 617-937-1665.